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CHARGE TRAPPING AND BUILT-IN FIELD STUDIES IN ELECTROREFLECTANCE OF A UN^{+} GaAs STRUCTURE

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(CHARGE TRAPPING AND BUILT-IN FIELD STUDIES IN GaAs)

ABSTRACT

A form of contactless electroreflectance, vacuum electroreflectance (VER), is used to quantitatively compare photoreflectance (PR) to electroreflectance (ER). It is found that the amplitude of the VER signal for a given applied modulation taken under CW laser illumination drastically decreases with increasing laser intensity. This new effect is studied as a function of frequency, and is explained in terms of the screening of the AC applied field by the surface charge, due to the presence of extra charged carriers in the depletion region. This effect is not present in contact forms of ER. It is also shown from a systematic comparison of PR and VER data that even for the lowest laser intensities which give an observable PR signal, the nature of the modulation in PR lowers the measured built-in field by an amount well outside the uncertainties in the determination of the field.

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Electroreflectance (ER) in its various forms is an important tool for materials characterization[1]. The need for techniques which do not make contact to the front surface of semiconductor samples has led to the widespread use of photoreflectance (PR)[2-7]. An alternative contactless ER (CER) technique developed in our laboratory[8,9] and elsewhere[10], employs a metal-insulator-semiconductor (MIS) structure. The electric field is applied capacitively. The sample serves as one plate, and a semitransparent electrode on a window forms the other plate, with a gap in between. In contrast with other schemes[10], the form developed in our group, vacuum electroreflectance (VER): *a)* is designed to operate under vacuum, allowing larger range of modulation; *b)* precise alignment and positioning is achieved with the use of piezo-electric motors; *c)* parallelism is diagnosed with the help of a HeNe interferometer, allowing precise measurement of the modulating electric field applied; and *d)* temperatures between 80 K and 370 K are achieved by Joule-Thompson cooling in conjunction with resistive heating.

We report here a previously unreported surface charge effect in VER (or CER, more generally) and investigate quantitatively the measurement of the built-in field (BIF) obtained from PR and ER data.

A laser shining on the surface of a semiconductor creates electron-hole pairs which decrease the existing built-in field (BIF). PR modulation should thus be similar to unipolar ER modulation in the forward direction, or, alternatively, bipolar ER modulation around a forward bias equivalent to that created by the average laser intensity. Consequently, PR can be simulated by VER under CW laser illumination of

half the intensity used for PR modulation. The same effects should be seen in data gathered using both techniques. PR/ER studies have been reported in previous papers[4-6]; however, they were done in a Schottky barrier configuration. VER provides a more direct check on the PR/ER issue since it preserves the open-circuit configuration of usual PR experiments. Comparison between VER data taken under CW HeNe laser illumination and PR data was made using a GaAs structure which has a large, position-independent BIF[11] due to the pinning of the GaAs Fermi level at the surface. This type of structure is often referred to as UN^+ (undoped-n^+)[4] or SIN^+ (surface-intrinsic-n^+)[3]. The sample studied consists of an MBE-grown undoped layer of GaAs of thickness 1100 Å, on top of a 1 μm n^+ ($\approx 10^{18}$ cm^{-3}) GaAs buffer layer grown on an n^+ ($\approx 10^{18}$ cm^{-3}) GaAs substrate. Thus the ER/PR spectra are characteristic of the high-field regime, and have as their signature a series of Franz-Keldysh oscillations (FKO). It is found that the buffer layer is essential for the observation of the FKO, presumably due to a better interface between the undoped and the heavily doped layers. The typical VER spectrum shown in Fig. (1) was obtained with a square-wave modulating field of 30 kV/cm, at 450 Hz.

The UN^+ structure allows a quantitative measurement of the built-in electric field of the sample. The quantity $(E_n-E_0)^{3/2}$, where E_n is the energy position of the n^{th} FKO extrema, and E_0 is the energy gap, has a linear dependence on the index[12] n. The slope of a straight-line fit to a graph of this quantity versus n is proportional to the BIF[4], as shown in Fig. (2). Maximum uncertainties in the reading of the positions of the maxima were estimated, and weighted least-square fits to the data were performed.

The weighting factor was calculated using standard error propagation formulas. The results were compared with those from unweighted fits, which are the kind of fits typically quoted in the literature. It was found that the precision of the fits was essentially the same, with the weighted fits consistently giving values for the BIF lower by about 1%. The inset of Fig. (2) shows the results of the fits for repeated VER runs on one piece of the sample under the same conditions on different days. The precision of determining the BIF from the data is about 0.2%. All the BIF values quoted henceforth are from the weighted fits.

The values of the BIF calculated from VER data taken under different intensities of CW laser illumination and from PR data at the same laser intensities are shown in Fig. (3). The PR data was plotted as a function of average laser intensity, for the reason discussed above.

A plot of the variation of the VER peak-to-peak signal amplitude from the first minimum to the first maximum as a function of laser intensity is shown in Fig. (4). This figure shows a dramatic signal decrease with increasing laser intensity, even though the applied modulation is the same for all runs. The signal is completely lost in the noise for the unattenuated CW HeNe laser ($\approx$130 μW/cm^2). No such reduction in amplitude was observed for a different piece, on which the modulating voltage was applied via a Schottky barrier.

Since the ER signal amplitude is proportional to the BIF, some decrease in the VER amplitude is expected due to the reduction of the BIF by the CW laser shining on the sample. For example, at 10 μW/cm^2, the BIF is reduced about 10%, as seen in

Fig. (3). A corresponding reduction in amplitude is expected. However, the VER amplitude is reduced by much more, a factor of three.

The influence of the modulation frequency on this reduction of the VER amplitude under CW laser illumination is shown in Fig. (5). The lower the modulation frequency, the stronger is the VER amplitude reduction for the same CW laser intensity. The measured BIF is independent of frequency. Note the decrease in the zero-laser-intensity value of the VER amplitude at 80 Hz. This suggests that even in the absence of a pump beam, the applied modulation is being screened at low frequencies. The frequency variation of the zero-laser-intensity VER amplitude is shown in Fig. (6). Consistent with this behavior, we have also observed an almost complete screening of an applied DC field[9] (the limit of zero frequency). (The data shown in Figures 4, 5 and 6 was taken on different pieces of the same wafer.)

These results can be explained in terms of the filling and emptying of surface traps. Since no contact is made to the front surface of the sample, the electrostatic boundary condition at the interface between the semiconductor and vacuum is

$$\Delta E_{appl} = \varepsilon \Delta E_{bi} + \frac{4\pi}{\varepsilon}\Delta\sigma_s \ , \tag{1}$$

where E_{appl} is the applied electric field, E_{bi} is the BIF, ε is the static dielectric constant, σ_s is the surface charge, and the Δ stands for the change in the respective quantities. Thus, any mechanism which increases the surface charge in times short compared to the modulation period will screen the applied modulating electric field. By screening

we mean that only part of the applied electric field goes into changing the BIF, the rest gets "lost" into changing the surface charge.

The modulation of the surface charge is a result of the modulation of the net current density which exists in the depletion region of a sample in the presence of a pump beam. The rate of change of the surface charge density equals the net current density, i. For small modulation, this current is proportional to the change in the built-in field E_{bi}, and the number of carriers n_{eff}, so we can write,

$$\frac{d}{dt}\left(\Delta\sigma_s\right) = i \propto \Delta E_{bi} n_{eff} \quad . \tag{2}$$

For a given i, there will therefore be more screening at lower frequencies, as a result of a greater charge moved to and from the surface, consistent with the results in Fig. 5. The number of carriers, and thus the net current intensity, increases with the laser intensity I. At a given modulation frequency, from Eq. (1), an approximate expression for screening of the applied electric field is

$$\Delta E_{bi} = \frac{a\Delta E_{appl}}{1 + cI}, \tag{3}$$

where a and c are constants of proportionality. A two-parameter fit to this equation is also shown in Fig. (4). A more detailed look into this explanation will be presented in a later paper.

It has been pointed out[3] that care must be taken in determining the low-field condition for PR measurements, the photovoltage leading to an erroneously reduced value of the BIF. To minimize even the effect of the probe beam, it is defocused on

the sample. Note that in Fig. (3) the PR data points are missing for the two lowest laser intensities which still produced a significant change in the BIF of the sample, as measured by VER data. This is a result of the amplitude of the PR signal decreasing with decreasing laser intensity and thus falling below the detection noise limit at those intensities. The measurement of the laser intensity is done by positioning a power meter at the same position relative to the fiber as the sample, as described in detail elsewhere[9]. The relative values are precise; the absolute values are upper-limit bounds of the intensity at the sample surface. The zero-intensity VER value is independent of the applied modulating field up to 30 kV/cm. After a careful investigation of the precision of the BIF measurement, as discussed, it became clear that the difference between the BIF values obtained from PR and VER data is significant and it does not come from the imprecision of determining the BIF. It is apparent that for such a sample the PR measurement in itself lowers the BIF by an amount substantially exceeding the uncertainty in its measurement. Hence, any BIF calculated straight from the PR data will depend on the intensity of the modulation. Moreover, there is a non-linear variation of the BIF with the modulation at low laser intensities ($\lesssim 1\mu W/cm^2$), so that even a linear fit does not extrapolate to the VER value, giving approximately 8% error for this sample. This effect should therefore be taken into account, especially for Fermi-level pinning measurements. For example, using PR, the BIF of a similar sample was compared in air and vacuum in ref. 7, and found to be higher in air. We performed low-modulation VER both in air and vacuum, and found the opposite result. We attribute this discrepancy to the high intensity of the laser used in PR modulation.

The lower BIF in vacuum which was reported, we believe to be an artifact of the factor of ten higher modulating laser intensity used in vacuum.

In conclusion, using the contactless VER technique we have compared PR with ER results on a UN$^+$ GaAs sample. We simulated PR by VER under CW laser illumination, and found that the amplitude of the VER signal with given applied modulation taken under CW laser illumination shows a drastic decrease as a function of laser intensity. We explain this in terms of the screening of the AC applied field by the surface charge due to the presence of extra charged carriers in the depletion region. This effect makes VER well suited for studying the dynamics of electron transfer across the depletion region. It is not present in contact forms of ER, and to the best of our knowledge is reported here for the first time. We also find that the nature of modulation in PR lowers the measured built-in field by an amount well outside the uncertainties in the determination of the field.

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REFERENCES

1. D. E. Aspnes, in *Handbook on Semiconductors*, edited by T. S. Moss (North-Holland, New York, 1980), Vol 2, p. 109 and references cited therein.

2. O. Glembocki, B. V. Shanabrook, N. Bottka, W. T. Beard, and J. Comas, Appl. Phys. Lett. **46**, 970 (1985).

3. H. Shen, M. Dutta, L. Fotiadis, P. G. Newman, R. P. Moerkirk, W. H. Chang, and R N. Sacks, Appl. Phys. Lett. **57**, 2118 (1990).

4. R. N. Bhattacharya, H. Shen, P. Parayanthal, F. H. Pollak, T. Coutts and H. Aharoni, Phys. Rev. **B 37**, 4044 (1988).

5. R. Glosser and N. Bottka, in *Proceedings of the Society of Photo-Optical Instrumentation Engineers*, (SPIE, Bellingham, 1987) Vol. 794, p. 88.

6. N. Bottka, D. K. Gaskill, R. S. Sillmon, R. Henry, and R. Glosser, J. Electron. Mater. **17**, 161 (1988).

7. X. Yin, H-M. Chen, F. H. Pollak, Y. Chan, P. A. Montano, P. D. Kirchner, G. D. Pettit, and J. M. Woodall, J. Vac. Sci. Technol. A **10**, 131 (1992).

8. S. L. Mioc, P. M. Raccah, and J. W. Garland, in the *Proceedings of the Society of Photo-Optical Instrumentation Engineers* (SPIE, Bellingham, 1992), Vol 1678, p. 296.

9. S. L. Mioc, PhD Thesis, University of Illinois at Chicago, 1994.

10. X. Yin and F. H. Pollak, Appl. Phys. Lett. **59**, 2305 (1991).

11. C. Van Hoof, K. Deneffe, J. De Boeck, D. J. Arent, and G. Borghs, Appl. Phys. Lett. **54**, 608 (1989).

12. D. E. Aspnes and A. A. Studna, 1973, Phys. Rev. **B 7**, 4605 (1973).

FIGURE CAPTIONS

Fig. 1 Typical VER data for square-wave modulation of 30 kV/cm at 450 Hz (no CW laser).

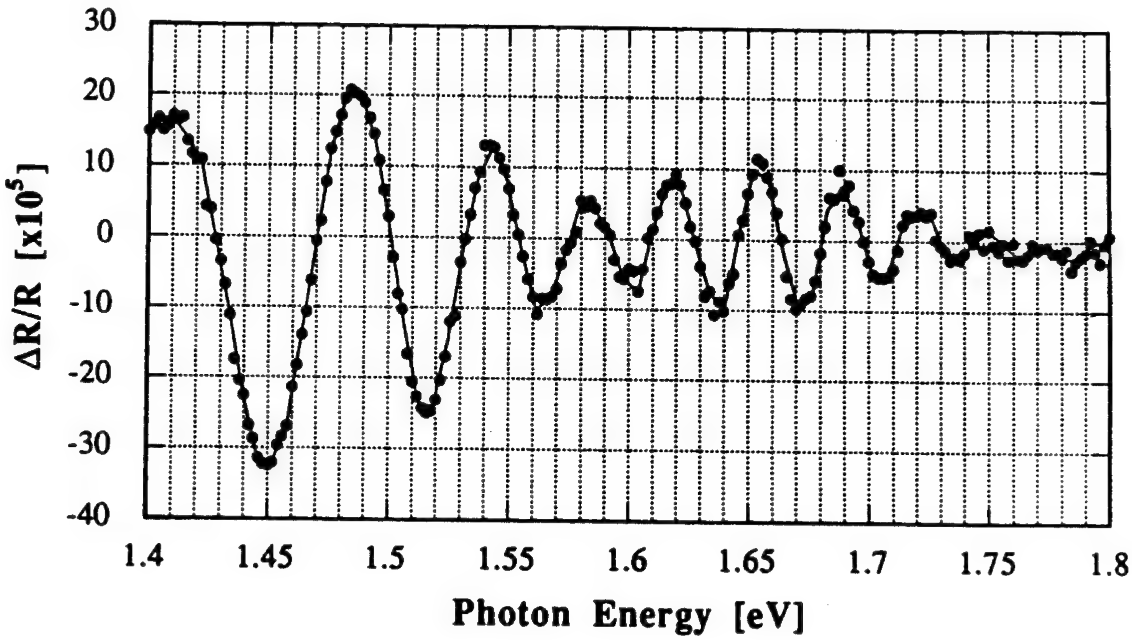
Fig. 2 Graph from which the built-in field values are calculated. The inset shows the built-in field determination from VER data taken under same conditions on different days.

Fig. 3 Values of the built-in field calculated from VER with optical bias and PR data at 450 Hz; the PR data was plotted as a function of CW average laser intensity. (VER data taken with square modulation of 30 kV/cm; PR data taken by chopping a HeNe laser) The VER values are independent of the modulating frequency for 80 Hz, 450 Hz and 2 kHz. The PR values were slightly higher at 80 Hz. Also shown is a straight-line fit to the PR data for $I > 2.5 \times 10^{-6}$ W/cm^2.

Fig. 4 Variation of the peak-to-peak amplitude of signal from VER signal with optical bias as a function of laser intensity at 450 Hz. Also shown is a fit to Eq. (3).

Fig. 5 Variation of the peak-to-peak amplitude of VER signal as a function of laser intensity for three modulation frequencies. Also shown are fits to Eq. (3).

Fig. 6 Variation of the peak-to-peak amplitude of VER signal as a function of modulation frequency (no CW laser).



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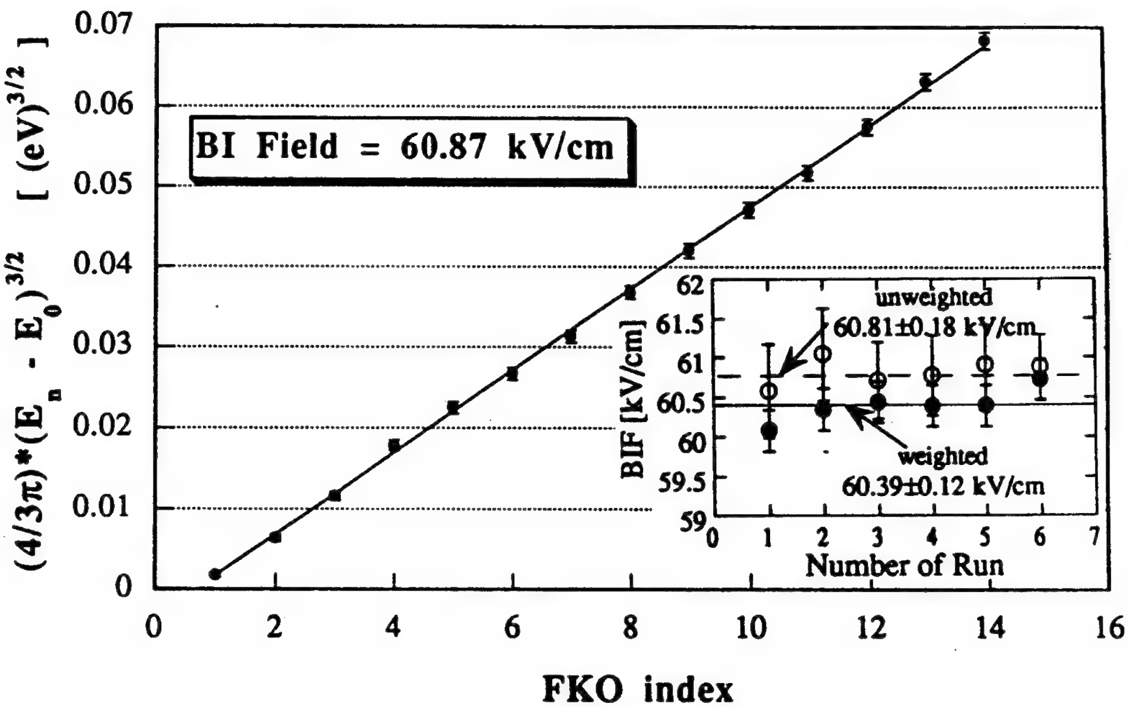

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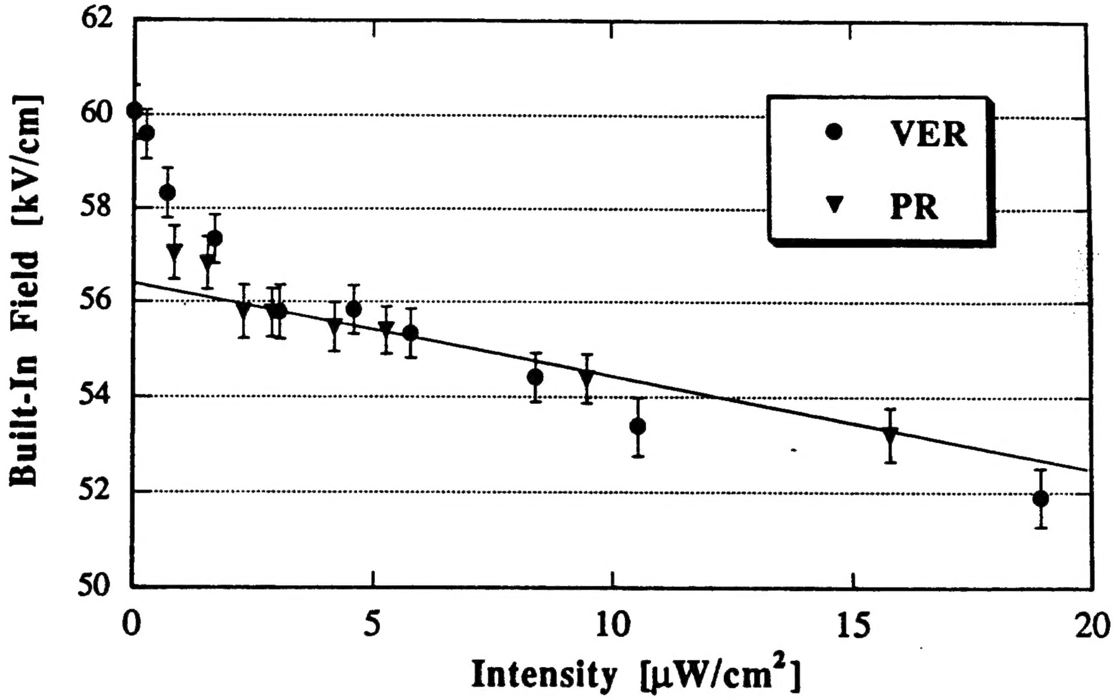

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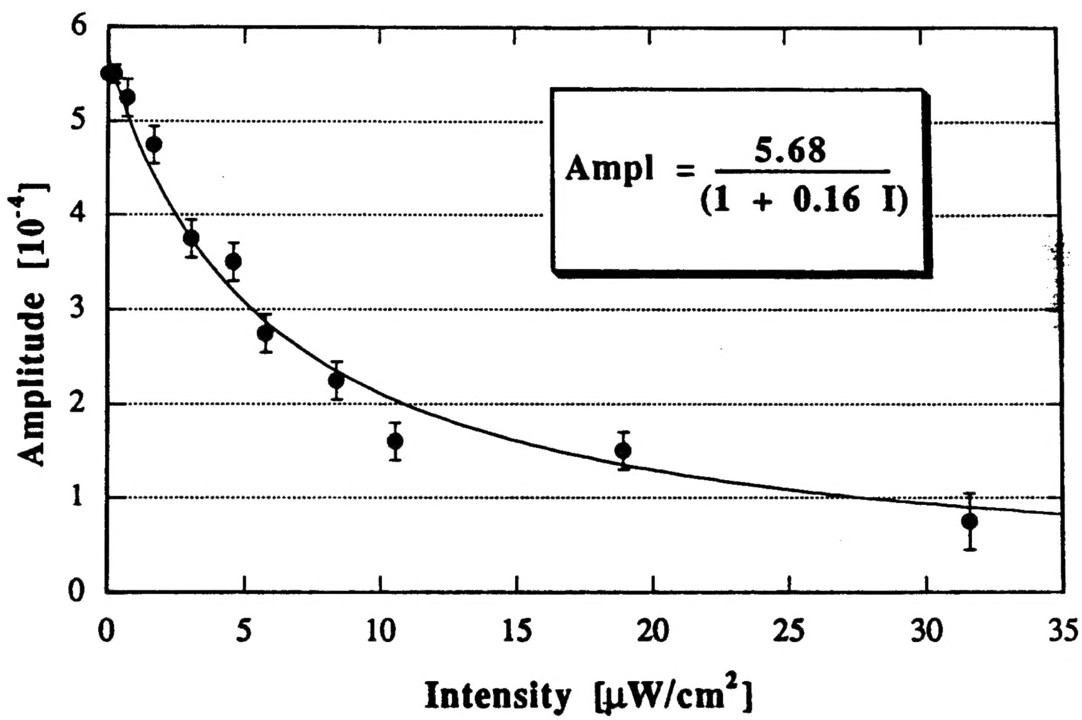

Fig. 4 Variation of the peak-to-peak amplitude of the VER signal with optical bias as a function of laser intensity at 450 Hz. Also shown is a fit to Eq. (3).

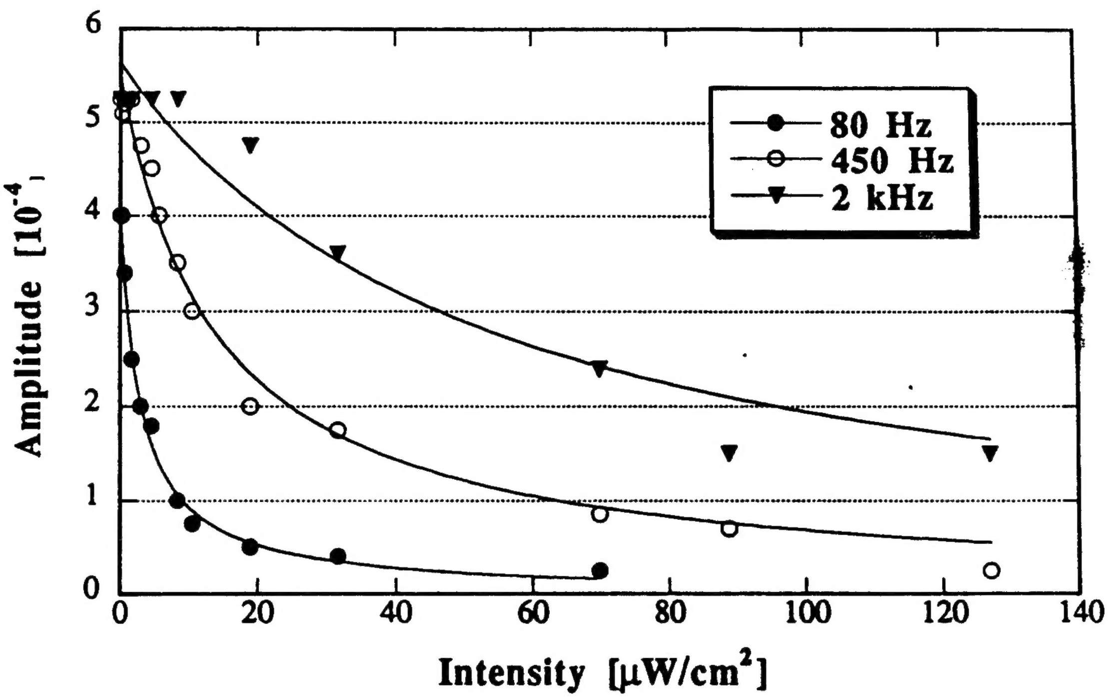

Fig. 5 Variation of the peak-to-peak amplitude of the VER signal as a function of laser intensity for three modulation frequencies. Also shown are fits to Eq. (3).

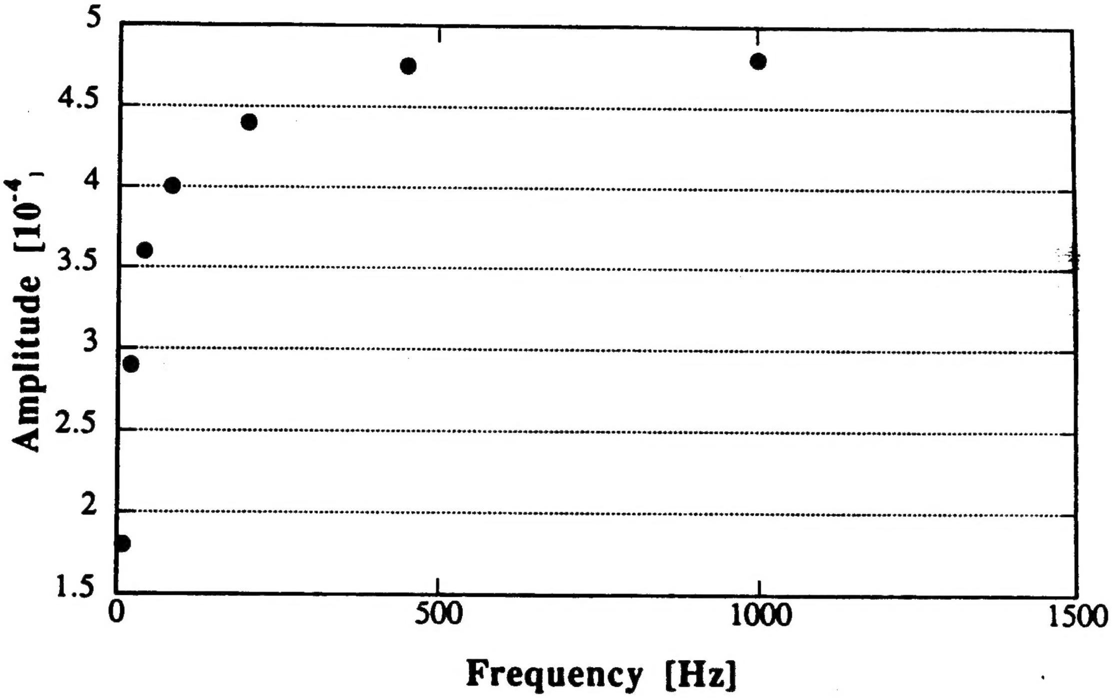

Fig. 6 Variation of the peak-to-peak amplitude of VER signal as a function of modulation frequency (no CW laser).